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Intrinsic Structure and Kinematics of the Sub-Parsec Scale Jet of M87

Y. Y. Kovalev

Max-Planck-Institut für Radioastronomie,
Auf dem Hügel 69, 53121 Bonn, Germany;
Astro Space Center of Lebedev Physical Institute,
Profsoyuznaya 84/32, 117997 Moscow, Russia

Abstract. We report new results from a sub-parsec scale study of the inner jet in M87 performed at 15 GHz with the Very Long Baseline Array. We have detected a limb brightened structure of the jet along with a faint 3 mas long counter-feature which we also find to be limb brightened. Typical speeds of separate jet features are measured to be less than 0.05 speed of light, despite the highly asymmetric jet structure and the implications of the canonical relativistic beaming scenario. The observed intrinsic jet structure can be described in terms of a two stream spine-sheath velocity gradient across the jet according to theoretical predications based on the recently discovered strong and variable TeV emission from M87. The jet to counter-jet flux density ratio is measured to be greater than 200. The observed intrinsic jet structure is broadly consistent with theoretical predictions of a spine-sheath velocity gradient suggested by recently discovered TeV emission from M87.

1. Introduction

The peculiar galaxy M87 in the Virgo cluster was among the first to be recognized as a powerful source of radio emission. M87 remains of great interest today, since there is strong observational evidence for a $3 \times 10^9\ M_\odot$ black hole located at the galactic nucleus thought to power the relativistic jet (Harms et al. 1994; Macchetto et al. 1997). Moreover, at a distance of only 16 Mpc, M87 is one of the closest radio galaxies, and as such it has one of the few jets which can be well-resolved on sub-parsec scales in a direction transverse to the flow.

In this paper we report on observations made with the NRAO Very Long Baseline Array (VLBA) at 2 cm wavelength. High dynamic range images constructed from observations made in the year 2000 describe the two-dimensional structure of the jet out to nearly 0.2 arcsec (16 pc) and show the presence of a faint counter-feature. These observations were complemented by regular observations made with lower sensitivity between 1995 and 2007 to study the outward flow within the inner part of the radio jet.

2. Jet Structure and Kinematics

M87 has been regularly observed with the VLBA since 1995 as part of the 2 cm VLBA survey (Kellermann et al. 1998) and the more recent MOJAVE program (Lister & Homan 2005). In these programs, at each epoch we observed

each source for a total of about one hour, with multiple observations spaced over a wide range of hour angle. For M87, we have obtained a total of 23 images between 1995 and 2007. Typically the rms noise in each image is about 0.3 mJy beam^{-1}. We have supplemented these multiple epoch images using VLBA 2 cm archive data from observations made at three epochs in 2000. These later observations were made with full tracks in hour angle each lasting about 10 hours using 2-bit recording at a 256 Mbps data rate.

In Figure 1, we show the 2 cm image constructed from a full track in hour angle made with the VLBA plus one VLA element on 08 May, 2000. A tapered (upper) image shows structure out to nearly 0.2 arcsec. The middle and lower plots present the naturally weighted CLEAN images of the inner jet. The beam is shown in the lower left hand corner of each map. The contours are plotted in successive powers of 2 times the lowest contour of 0.2 mJy/beam. The peak intensity of the naturally weighted image is 1.00 Jy beam^{-1}, the rms noise is 64 μJy beam^{-1}, and the corresponding dynamic range is better than 15,000 to 1. The jet appears bifurcated, starting at about 5 mas (0.4 pc) from the core, characteristic of a single limb brightened cylindrical or conical jet. The M87 jet appears highly collimated, with re-collimation observed between 2 pc where the opening angle is about 16°, and 12 pc where the opening angle is only 6° to 7°. Figure 1 also shows the existence of weak 3 mas long structure extending away from the bright core toward the southeast. Indications of this counter feature were first suggested by Ly et al. (2004) on the basis of their 7 mm VLBA observations. This counter-feature also appears clearly bifurcated. The two plots of the intensity profile cuts of the counter-jet and the jet clearly show the limb brightening (Figure 1).

For several reasons we believe that the eastern extension may be the counter-jet. Based on their higher resolution 7 mm image, Ly et al. (2007) have also detected the counter feature and have argued that the true base of the jet cannot be offset by more than 2 mas from the bright core; whereas we have detected the counter-feature to be at least 3.1 mas long. Also, we note strong circular polarization at a fractional level of $-0.5\% \pm 0.1\%$ was detected by Homan & Lister (2006) coincident with the flux density peak, suggesting that this region of the jet has an optical depth near unity (e.g., Jones 1988) which is characteristic of jet cores. Since the eastern feature is more than 20 times fainter than the bright 1 Jy feature we have identified with the core, it seems unlikely that it could be the actual core. However, considering that no other radio jet has been observed with comparable linear resolution, sensitivity, and dynamic range, we cannot exclude the possibility that we are seeing the detailed structure of the optically thick core of the jet, and that the counter-jet itself is not detected. Multi-frequency VLBI observations of the core region are needed to determine if the eastern feature has a flat spectrum characteristic of an optically thick synchrotron core or steep spectrum as seen in other transparent jets.

We find no evidence for motions faster than $0.05c$ within the inner 20 mas (1.6 pc). The fastest jet speed observed is only $0.024 \pm 0.004c$, while the counter-jet apparently moves outward at $0.009 \pm 0.002c$. Other features appear essentially stationary over the twelve years that they have been observed, with nominal upper limits to their speed of about $0.05c$. All features were detected at between 16 and 23 different epochs. We believe that this interpretation is more robust

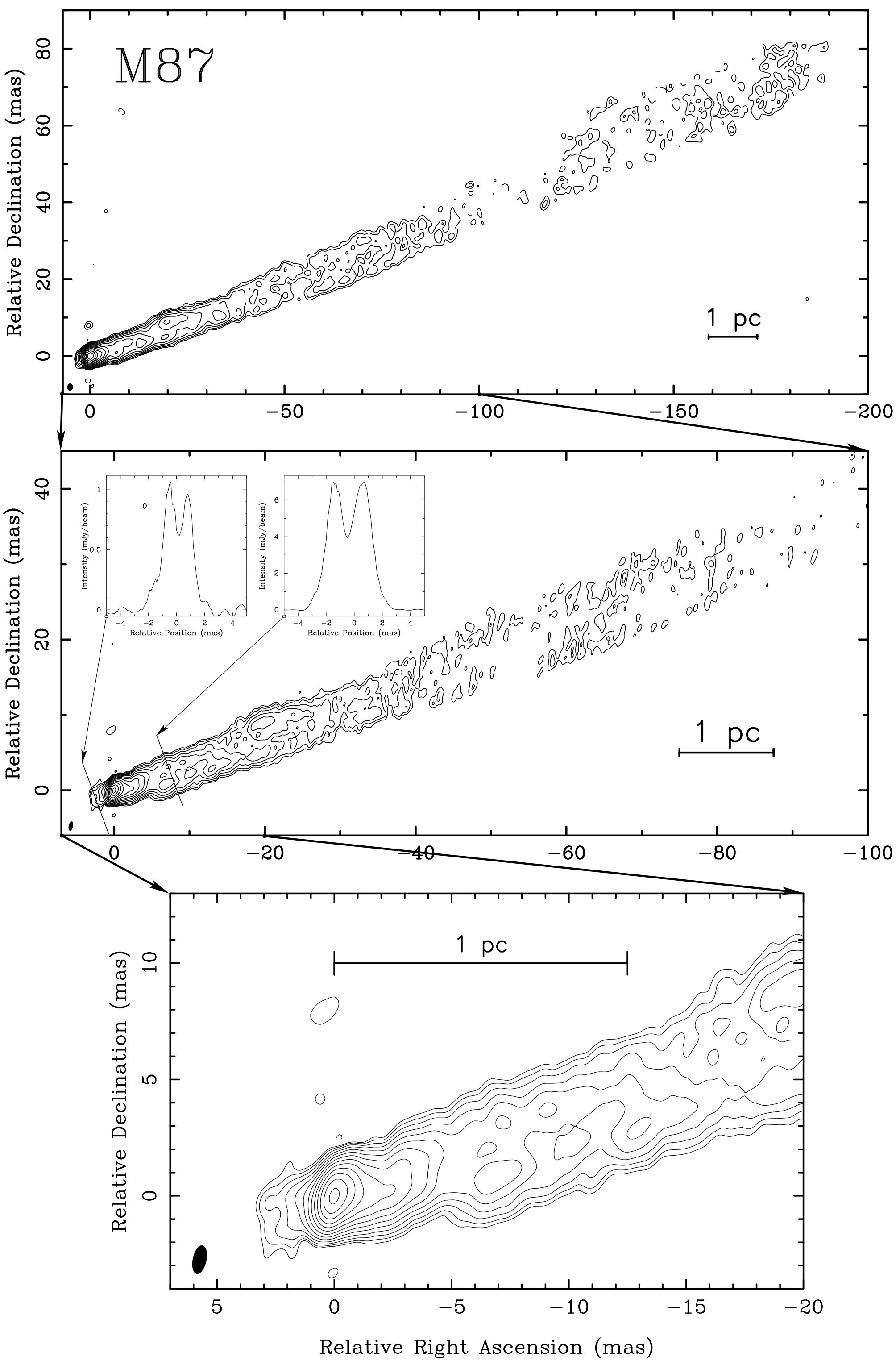

Figure 1. VLBA 2 cm image of the M87 jet.

than other radio measurements which typically used only two or three epochs. Of course, we cannot rule out the possible existence of a smooth relativistic flow with no propagating shocks or other patterns.

3. Discussion

Considering that the Doppler boosted relativistic jet of M87 appears one-sided out to kiloparsec scales, the absence of any clear motions in the inner jet is somewhat surprising. We measure a jet to counter-jet flux density ratio of between 10 and 15 (in the year 2000) at a position between 0.5 and 3.1 mas from the core, and a lower limit of 200 between 3.1 to 6.0 mas away. Assuming that the jet is intrinsically bidirectional and symmetric and that the bulk velocity flow is the same as the pattern motion, our maximum reliable observed speed of $\beta_{\rm app} = 0.024 \pm 0.004$ would imply a jet to counter-jet ratio near unity for the commonly accepted viewing angle of $\sim 40^\circ$ (e.g. Owen et al. 1989; Reid et al. 1989). If the jet and counter-jet are intrinsically symmetric and oriented at an angle of 30° to 40° to the line of sight, the observed jet to counter-jet flux density ratios imply that the intrinsic flow speed, β, is 0.5 to 0.6 between 0 and 3.1 mas from the core and increases to $> 0.9c$ beyond 3.1 mas. We conclude that the jet is either intrinsically asymmetric, or there are no moving features within a rapidly flowing plasma.

Apparent limb brightening is predicted from analytic and numerical modeling of relativistic jets (Aloy et al. 2000; Perucho et al. 2007) and can be reproduced in terms of Kelvin-Helmholtz instability, which is seen in extragalactic jets both at kiloparsec (M87, Lobanov et al. 2003) and parsec scales (3C273, Lobanov & Zensus 2001). Limb brightening can be particularly pronounced when the jet opening angle is greater than the beaming angle (Gopal-Krishna et al. 2006) and especially if there is a velocity gradient across the jet (Gopal-Krishna et al. 2007). A two layer "spine-sheath" model has been suggested to explain the existence of observed strong TeV emission from BL Lacs with apparently slow moving radio jets (Chiaberge et al. 2000; Piner & Edwards 2004; Giroletti et al. 2004). Stawarz & Ostrowski (2002) and Ghisellini et al. (2005) have considered a two component jet having a fast spine which produces the gamma ray emission by inverse Compton scattering of the radio photons from a surrounding slow layer or sheath. Spine-sheath models have also been discussed by Bridle (1996), Swain et al. (1998), Attridge et al. (1999), Laing & Bridle (2002), and Cohen et al. (2007). The central gap seen in our VLBA image of M87, as well as observed TeV emission (Aharonian et al. 2006) combined with the lack of measurable motion within the inner 1.6 pc (§2.) appears to support this two component model.

The recently reported detection of strong variable TeV emission from M87 (Aharonian et al. 2006) also presents a problem, since unless the radiating plasma has a large Doppler factor, energy losses due to $\gamma - \gamma$ pair production will extinguish the gamma ray emission (e.g., Dondi & Ghisellini 1995). However, we do not find any evidence for a fast moving jet in M87 close to the central engine, but the observed TeV emission can be explained in terms of a dual layer model with a fast inner jet and a slower moving outer layer (Ghisellini et al. 2005). In this picture, the inner jet is beamed away from us and is thus not seen in our

VLBA images, and we only observe the slower outer layer. However, even the slow outer layer must move at at least $\beta > 0.5$–$0.8c$ to be consistent with the jet to counter-jet flux density ratio as discussed earlier in this section.

4. Summary

VLBA images of the inner radio jet of M87 show a limb brightened structure characteristic of a two stream spine-sheath velocity gradient across the jet, as predicted from the recently discovered strong and variable TeV emission and numerical modeling. Multi-epoch VLBA observations of seven separate jet features made since 1995 show typical velocities less than a few percent of the speed of light, contrary to what might be expected from the highly asymmetric jet structure and the canonical relativistic beaming scenario. We have also found a weak feature, located on the opposite side of the bright core from the jet which also appears limb brightened. We believe this may be the beginning of a counter-jet, but cannot exclude the possibility that we are seeing the detailed structure of the core. We measure a jet to counter-jet flux density ratio ranging from 10–15 close to the core to more than 200 between 3 and 6 mas away. Considering the lack of observed motion in the inner jet, and the large jet to counter-jet ratio, we conclude that either the jet of M87 is intrinsically asymmetric or that the bulk plasma flow is much greater than any pattern or shock propagation.

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